SUBJECTIVE RESPONSE TO SIMULATED SONIC BOOMS WITH GROUND REFLECTIONS

by

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SUMMARY

The Sonic Boom Simulator at NASA Langley Research Center was used to (1) quantify subjective loudness of simulated composite sonic booms, each of which was comprised of a simulated direct (non-reflected) boom combined with a simulated reflection of the direct boom, and (2) evaluate several metrics as estimators of loudness for these composite booms. The direct booms consisted of selected N-wave and minimized signatures having front-shock rise times of 3, 6, and 9 milliseconds and durations of 300 milliseconds. Delay times of the reflected booms ranged from 0 to 12 milliseconds. Subjective loudness results indicated that composite booms formed using reflections with nonzero delay times were generally rated as being less loud than composite booms containing non-delayed reflections. The largest reductions in loudness occurred when delay times were equal to the front shock rise times of the direct booms and were, in some cases, equivalent to reductions in Perceived Level of 6 to 7 dB. Results also showed Perceived Level to be an effective metric for assessing subjective loudness effects for the composite signatures. This was confirmed by statistical analysis, which showed that, for equal Perceived Level, no significant differences existed between the subjective loudness responses to composite booms containing reflections with zero delay and those containing reflections with non-zero delays.

INTRODUCTION

A series of laboratory tests (references 1-6) to quantify subjective response to a wide range of simulated N-wave and minimized (shaped) sonic boom signatures have been conducted at NASA Langley Research Center. The boom signatures used in these tests were presented as if they were heard in free field conditions, with no reflections from nearby surfaces. In realistic situations, however, persons exposed to sonic booms will either be indoors, surrounded by relatively close reflecting surfaces, or outdoors, where reflecting surfaces may be present at varying distances from the observer. In the outdoor situation a human observer will hear at least two booms: one directly propagated from the aircraft (direct boom) and one reflected from the ground (reflected boom). The reflected sonic boom will combine with the direct boom to produce a composite boom that is the summation of the two. It is this composite signature that will be perceived and judged by an observer. If the time interval between a direct and reflected boom is less than the integration time of the ear, the two will be perceived as a single event. Reflections that arrive after a delay greater than the integration time of the ear may be heard as separate events.

Field recordings of sonic booms are generally made using flush-mounted microphones on the ground plane, resulting in a reflection from the surrounding surface that is coincident with the direct boom and causing a doubling in pressure. Estimates of loudness based upon these measurements may overpredict the loudness actually perceived by an observer. A factor that will significantly influence the shape (and consequently, subjective perceptions) of a composite signature is the delay time of the ground-reflected boom. This is the time by which the reflected boom lags the direct boom and is a function of observer height and angle of incidence of the shock wavefront. Loudness calculations (ref. 7) of composite booms, each of which was comprised of a direct boom combined with a single ground-reflected boom with a specific delay time, showed that composite booms with delay times other than zero could be significantly quieter than those with zero delay time. (Composite booms with zero delay time correspond to booms measured by flush-mounted microphones.) This effect, however, has not been verified experimentally. Also, the ability of various metrics to account for subjective effects of ground-reflected booms has not been experimentally investigated.

The purpose of this paper is to present the results of an experimental investigation to (1) quantify the subjective effects due to ground reflections of simulated N-wave and minimized boom signatures; and (2) assess the ability of several metrics to account for delay time effects. The metrics of interest were: Steven’s Mark VII Perceived Level, Zwicker Loudness Level, A-weighted Sound Exposure Level, C-weighted Sound Exposure Level, and Unweighted Sound Exposure Level. The test stimuli consisted of composite signatures obtained by summing a direct boom and a single delayed reflection of the direct boom.

EXPERIMENTAL METHOD

Sonic Boom Simulator

The experimental apparatus used was the Langley Research Center’s Sonic Boom Simulator. Construction details, performance capabilities, and operating procedures of the simulator are given in reference 1. The simulator, shown in figure 1, is a person-rated, airtight, loudspeaker-driven booth capable of accurately reproducing user-specified sonic boom waveforms at peak sound pressure levels up to approximately 138 dB. Input waveforms are "predistorted" to compensate for nonuniformities in the frequency response characteristics of the booth and sound reproduction system.

Test Subjects

Forty-eight test subjects (30 female, 18 male) obtained from a pool of local residents were used. Ages of the test subjects ranged from 18 to 61 years with a median age of 31.5 years. All subjects underwent audiometric screening prior to the test in order to verify normal hearing.

Experimental Design

Test Stimuli

To assist in understanding the nature of the test stimuli, it is useful to define several terms that are used in the following discussion. The term "direct boom" refers to a simulation of a sonic boom that is received directly from an aircraft and does not contain reflections. The term "reflected boom" refers to the waveform generated as a result of a simulated ground reflection of the direct boom. It would arrive at the ear of an observer after a short time delay governed by the angle of incidence of the direct boom and the height of the observer. The term "composite boom" refers to the simulated waveform resulting from summation of the direct and reflected booms. The reflected boom lags the direct boom by a short time interval defined as "delay time." The term "boom type" refers to the shape of the direct boom.

In the present study, each simulated composite signature was defined by the combination of a direct boom with a single reflection of the direct boom with no change in phase or amplitude between the two waveforms. Twenty-four distinct direct booms were used. These were obtained by considering factorial combinations of two boom types, three front shock rise times, and four peak overpressures. Each distinct direct boom was then combined (separately) with each of six reflections (each having a different delay time) of that direct boom. Thus, each direct boom provided six unique composite booms, one for each of the six delay times. This resulted in a total of 144 test stimuli. The two shape categories used to define boom type were N-wave and front-shock minimized. In a real situation the term "front-shock minimized" refers to a boom which is shaped at the source to be of a certain form at the ground. In the present study the desired forms of the front-shock minimized signatures were directly realized by using the waveform generation capabilities of the sonic boom simulator. The particular front-shock minimized boom shapes selected were characterized by a front shock overpressure to peak overpressure ratio of 0.5 and secondary rise time of 60 milliseconds. The two boom types are illustrated in figure 2. These are idealized shapes which make no attempt to incorporate distortions due to propagation through a real atmosphere. Front shock rise times were 3, 6, and 9 milliseconds for each boom type, and duration for all direct booms was 300 milliseconds.

The six values of delay time used to generate the six composite booms corresponding to each combination of boom type and rise time are given in Table 1. Note that delays of 0, 3, and 12 milliseconds were common to all combinations. (A delay of zero corresponds to a reflected wave coincident with the direct wave, resulting in the same wave shape with a doubling of overpressure.) The remaining three values of delay time for each combination were: delay time = front shock rise time; and delay time = front shock rise time ± 1 millisecond. These were selected on the basis of predicted delay time effects (discussed in a later section). The direct booms having a 3-millisecond rise time included a delay of 8 milliseconds. Nominal composite signatures are displayed in figure 3.

Scaling Method

The scaling method used was magnitude estimation. Its applicability to sonic boom was demonstrated in reference 6 which verified that subjects could, and did, make valid ratio judgment of sonic boom loudness. The procedure used is summarized as follows: A sonic boom stimulus, designated as the standard, was presented to a subject. The standard was assigned a loudness value of 100 by the experimenter. The standard was then followed by three comparison booms. The task of a subject was to rate the loudness of each comparison boom as compared to the standard. For example, if a subject felt that a comparison boom was twice as loud as the standard, then the subject would assign it a value of 200. If the comparison boom was felt to be only one-fourth as loud as the standard, then the subject would assign it a value of 25. After three comparison stimuli were judged, the standard was repeated and another three comparison booms were evaluated. This procedure was repeated until all booms within a test session (and all test sessions) were completed. The subjects were free to assign any number of their choosing (except negative numbers) to reflect their loudness opinions. The instructions explaining how to use the magnitude estimation procedure are given in Appendix A.

Test Structure

The 144 test stimuli were randomly assigned to four sessions of 36 booms each. This test was conducted concurrently with another test, which consisted of 90 test stimuli, divided into two sessions of 45 booms each. To reduce order effects, the booms within each session were presented in both forward and reverse sequence. This resulted in a total of 12 sessions, which were ordered for presentation to the individual subjects using a balanced Latin Square design.

Test Procedure

Subjects arrived at the laboratory in groups of three, with one group in the morning and one group in the afternoon on any given day. Upon arrival at the laboratory, each group was briefed on the overall purpose of the experiment, system safety features, and their rights as test subjects. A copy of these briefing remarks is given in Appendix B. The subjects were then given specific instructions related to the test procedure to be followed and in the use of the magnitude estimation procedure (Appendix A). At this point the subjects were taken individually from the waiting room to the sonic boom simulator. At the simulator the scaling procedure was reviewed and the subject listened to several stimuli, played with the simulator door open, in order to become familiar with the type of sounds she/he would be asked to evaluate. The subject was then given a practice scoring sheet and seated in the simulator with the door closed. A practice session was then conducted in which the subject rated a set of stimuli similar to those used in the actual test sessions. Upon completion of the practice session, the scoring sheet was collected and any questions were answered. The first test session was then conducted. After all subjects completed the first session, they were then cycled through the remaining sessions. No further practice sessions were given.

Data Analysis

The boom pressure time histories measured within the simulator were computer processed to calculate sound exposure level in terms of three frequency weightings and to calculate two loudness metrics. The sound exposure level metrics were: unweighted sound exposure level (L_{UE}), C-weighted sound exposure level (L_{CE}), and A-weighted sound exposure level (L_{AE}). The loudness metrics were Stevens Mark VII Perceived Level (PL) and Zwicker Loudness Level (LLZ). Perceived Level was calculated using the method presented in reference 8.

The central tendency parameter used to characterize the magnitude estimation scores was the geometric mean of the magnitude estimates for each stimulus. It is customary (see reference 9, for example) to use geometric averaging with magnitude estimation since the distribution of the logarithms of the magnitude estimates is approximately normal. Furthermore, subjective loudness is a power function of the physical intensity of a sound. Such a power function is linear when expressed in terms of the logarithms of the subjective loudness and sound pressure level.

DISCUSSION OF RESULTS

Metric Considerations

The overall performance of each metric as a loudness estimator was assessed by computing two sets of parameters using the obtained subjective data. The first set of parameters was the correlation coefficients between the logarithm of the geometric means and the levels of each metric. The metric levels were calculated from boom measurements made within the simulator. The correlation coefficients are measures of the degree of relationship between each metric and the obtained subjective ratings. The second set of parameters was the standard errors of estimate of the best-fit linear regression lines describing the relationship between subjective ratings and levels of each metric. These represent the prediction accuracies of each metric. The smaller the standard error of estimate, the greater the prediction accuracy. Both of these parameters were calculated for the complete stimuli set and for each boom type. The correlation coefficients are displayed in Table 2 and the standard errors of estimate in Table 3. Scatter plots showing the subjective data for each metric are shown in figure 4.

Examination of Tables 2 and 3 indicates that PL correlated highest with subjective ratings and exhibited the lowest standard errors of estimate (least scatter) for all boom groupings. This is illustrated by inspection of the scatter diagrams of figure 4. The LLZ and L_{AE} metrics also correlated highly with subjective ratings, but had larger standard errors of estimate than PL. The L_{CE} and L_{UE} metrics' correlations were significantly lower, and their standard errors of estimate significantly higher, than those of the other metrics. These results indicate that PL was the best estimator of loudness for the composite booms. They also support the recommendation of reference 4 that PL be selected as the metric of choice for general use in assessing sonic boom subjective effects.

Reflected Boom Effects

Delay vs No Delay

The above discussion indicated that the PL metric best accounted for the loudness effects introduced by reflected booms of varying time delay. This implies that the subjective ratings for the composite booms with non-delayed reflections would not differ significantly from those with delayed reflections when expressed in terms of PL. To verify this, the subjective loudness ratings of the composite booms with delayed and non-delayed reflections were compared. This comparison is presented in figure 5, which shows the linear regression lines for each case. Inspection of figure 5 indicates that, when expressed in terms of PL, the subjective responses for the composite booms with delayed and non-delayed reflections were virtually identical. Statistical analysis confirmed that the two regression lines did not differ. This does not imply, however, that the loudness of composite sonic booms was independent of delay time. It simply means that any such effects were accounted for by PL.

<u>Effect of Delay Time</u>

Theoretical predictions using the method of reference 8 indicate that delay time has a significant effect on loudness. For example, figure 6 shows predicted PL as a function of delay time for a number of idealized composite signatures derived from N-waves having various rise times. These predictions indicate that composite booms containing delayed reflections would be less loud than those containing non-delayed reflections, and that maximum loudness reductions would occur when delay times were equal to the rise times of the constituent N-waves (indicated by the "dips" in the curves of figure 6). These predictions do not agree with those of reference 7, particularly with regard to the locations of the "dips" in the loudness curves. Differences between the two methods are probably due to the fact that reference 7 used the envelope of the energy maxima of the sonic boom spectra to calculate 1/3 octave band levels (and thus loudness levels), whereas the present study used the spectra computed by passing complete time histories through an FFT alogorithm.

Two approaches for quantifying the effects of delay time were considered. The first approach determined the effects of delay time on measured PL (calculated from microphone measurement of each signature within the simulator) and was therefore independent of the subjective ratings. The method used was to perform a series of dummy variable analyses using, for each analysis, the set of six composite signatures for a given direct boom. The dependent variable in each analysis was measured PL and the quantitative independent variable was overpressure. The qualitative independent variable was delay time, which consisted of six classes corresponding to the six delay times of a reflected boom. An advantage of dummy variable analysis is that differential effects on the dependent variable due to the various classes of the qualitative independent variable are directly obtained. The differential effects are determined relative to a selected class of the quantitative independent variable. In the present case, the differential effects on measured PL (dependent variable) of delay time (qualitative independent variable) relative to the zero delay time condition were determined. These are designated as ΔPL_{meas}. Thus each ΔPL_{meas} represents, for a given direct boom and specific delay time, the difference between the measured PL of the composite signature containing the delayed reflection and the measured PL of the composite signature containing the non-delayed reflection. Each difference is expressed in terms of dB(PL) units.

The second approach determined delay time effects using the subjective ratings as the dependent variable. The delay effects based upon the subjective ratings were then compared to those obtained using measured PL in order to validate and assess the effectiveness of measured PL in accounting for delay effects. The dummy variable analyses were performed in the manner described above except that the dependent variables were the logarithms of the geometric means of the subjective ratings. All other variables remained the same. In this case the differential effects due to delay time were in terms of the subjective ratings. To make meaningful comparisons to delay time effects determined using measured PL, it was necessary to convert the differential ratings to equivalent differential PL values. This conversion was accomplished by (a) determining the equation of the linear regression line relating PL to the logarithm of the geometric means of the subjective ratings for the composite booms and (b) multiplying each differential rating by the slope of the regression line. The resulting equivalent differential PL values were designated as ΔPL_{rating}. Thus, for each direct boom, a set of five values of ΔPL_{meas} and five values of ΔPL_{rating} were determined. (For zero delay $\Delta PL_{meas} = \Delta PL_{rating} = 0$, by definition.)

Comparison of the delay time effect in terms of ΔPL_{rating} and ΔPL_{meas} is given in figures 7(a) and 7(b) for each boom type (N-wave or minimized) and rise time combination. The solid lines in each figure represent the delay effect based upon the subjective ratings, and the dotted line represents the delay effect based upon measured PL. These figures show that the overall trends for both ΔPL_{meas} and ΔPL_{rating} agree reasonably well with the predicted effects shown in figure 6. Specifically, the composite booms containing delayed reflections were generally less loud than those containing non-delayed reflections. This result was not unexpected, since composite booms with zero delay were characterized by a doubling of peak overpressure and retention of the original rise time characteristics of the component booms. Composite booms containing delayed reflections did not achieve a doubling of peak overpressure, except for the special cases when delay time of a reflected boom was equal to the rise time of the corresponding direct boom. For each of these cases the rise time of the composite boom was double that of the original direct boom. This resulted in sizeable loudness reductions relative to the composite booms containing non-delayed reflections. This effect is illustrated in figure 7 by the dip in each curve when delay time was approximately equal to the rise time of the direct boom. These dips ranged from about -4 to -7 dB(PL), depending upon the particular direct boom of interest. Note that the locations of these dips agree well with the predictions of figure 6.

The data of figure 7 also show that measured PL effectively "tracked" the delay time effect based upon the subjective ratings. For example, ΔPL_{meas} and ΔPL_{rating} agreed well in both shape and magnitude for all minimized booms and for the set of N-wave booms with a rise time of 9 msec. Results for the remaining N-waves (rise times of 3 and 6 msec) generally agreed with respect to the shape of the delay effect, but ΔPL_{meas} tended to overestimate loudness reductions by as much as 1 to 2 dB(PL) relative to those reported by the subjects. The reason for this is unclear. Overall, however, PL performed very well as an estimator of subjective loudness for sonic booms containing single reflections of varying time delay. This further supports the recommendation of reference 4 that PL be selected as the metric of choice for assessing sonic boom subjective effects.

CONCLUDING REMARKS

The sonic boom simulator of the Langley Research Center was used to (1) quantify the effects of delay time on subjective loudness of simulated composite sonic booms consisting of a direct boom combined with a single delayed reflection of that direct boom, and (2) evaluate several metrics as loudness estimators of these composite booms. The direct booms consisted of selected N-wave and front-shock minimized signatures having front shock rise times of 3, 6, and 9 milliseconds. Six values of delay time were used for each reflected boom. Minimum and maximum delay times for each were 0 and 12 milliseconds, respectively. The remaining four delay times were selected to include, and encompass, the original rise times of the direct booms. Specific findings and comments obtained in this study are summarized as follows:

1. The best metric for use in predicting the loudness of composite booms consisting of combined direct and reflected signatures was Perceived Level, PL. This metric correlated highest with subjective loudness ratings and was the most accurate loudness estimator.
2. Subjective responses for composite booms containing delayed reflections and for those containing non-delayed reflections were statistically identical when expressed in terms of PL. Thus, PL effectively accounted for the overall effects due to delay time.
3. Loudness ratings of composite signatures containing delayed reflections were generally lower than the ratings for the composite signatures containing non-delayed reflections. This is because a

composite boom comprised of a direct boom combined with a non-delayed reflection of the direct boom is characterized by a doubling of peak overpressure while retaining the rise time of the constituent booms. Thus, loudness estimates derived from flush-mounted microphone measurements will generally be conservative.

4. Maximum loudness reductions for composite booms containing delayed reflections occurred when the delay time of a reflected boom was approximately equal to the rise time of the direct boom. These reductions ranged from about -4 to -7 dB(PL), depending upon the particular direct boom considered, and were due to an effective doubling of front shock rise times for these special cases.
5. The trends associated with the delay effects (loudness reductions) based on measured PL agreed well with those based on subjective ratings. This demonstrated the ability of PL to effectively account for detailed delay time effects.
6. The ability of PL to account for overall and detailed delay time effects further supports the selection of Perceived Level as the metric of choice for assessing sonic boom subjective effects.

APPENDIX A

Subject Instructions

This test will consist of six test sessions. Prior to the first test session each of you will be taken individually to the simulator where you will listen to sounds that are similar to those you will be asked to rate. We will then place you in the simulator and a practice scoring session will be conducted. Upon completion of the practice session we will collect the practice rating sheets and answer any questions you may have concerning the test. At this point two test sessions will be conducted. You will then return to the waiting room while the other members of your group complete a similar test. You will return to the simulator two more times to complete the remaining test sessions.

During a test session we will play a series of sonic booms over the loudspeakers in the door of the simulator. The first sonic boom that you hear, and every fourth boom thereafter, will be a **REFERENCE** boom that you will use to judge how loud the other booms are. In order to help you keep track of which boom is the **REFERENCE** boom, it will always be preceded by a short beep. The **REFERENCE** boom will remain the same throughout the test. Your task will be to tell us how loud each of the other booms are as compared to the **REFERENCE** boom. You will be provided rating sheets for use in making your evaluations. The ratings sheets will indicate when a **REFERENCE** boom will be played and the sequence of **REFERENCE** and other booms will be organized as follows:

```
<---------------------beep
R=100 <------------------reference
1.________
2.________
3.________
   <---------------------beep
R=100 <------------------reference
4.________
5.________
6.________
```

The scoring procedure will be as follows: The short beep will indicate to you that the boom which follows is the **REFERENCE** boom. Please listen to it carefully because you will compare the other booms to it. For this purpose the **REFERENCE** boom will be assigned a loudness value of 100. Thus you do not score the **REFERENCE** boom because it will always be equal to 100. You will then hear a sequence of three comparison booms. After listening to each comparison boom you should decide how loud you think it is relative to the **REFERENCE** boom and assign it a number accordingly. This number will be entered on the appropriate line of the scoring sheet. For example, if you feel the comparison boom is three times louder than the **REFERENCE** boom then you would give it a loudness score of 300. If you think the comparison boom is only one-fourth as loud as the **REFERENCE** boom you would give it a loudness score of 25. You may choose any number you wish as long as it faithfully represents your impression of the relative loudness of the comparison and **REFERENCE** booms. After evaluating three comparison booms in this manner you will hear the beep again, followed by the **REFERENCE** boom and three more comparison booms. This will be repeated within a test session until the test session is completed. Remember! There are no right or wrong answers. We are interested only in how loud the booms sound to you.

APPENDIX B

General Briefing Remarks

You have volunteered to participate in a research program designed to evaluate various sounds that may be produced by certain aircraft. Our purpose is to study people's impressions of these sounds. To do this we have built a simulator which can create sounds similar to those produced by some aircraft. The simulator provides no risk to participants. It meets stringent safety requirements and cannot produce noises which are harmful. It contains safety features that will automatically shut the system down if it does not perform properly.

You will enter the simulator, sit in the chair, and make yourself comfortable. The door will be closed and you will hear a series of sounds. These sounds represent those you could occasionally hear during your routine daily activities. Your task will be to evaluate these sounds using a method that we will explain later. Make yourself as comfortable and relaxed as possible while the test is being conducted. You will at all times be in two-way communication with the test conductor, and you will be monitored by the overhead TV camera. You may terminate the test at any time and for any reason in either of two ways: (1) by voice communication with the test conductor or (2) by exiting the simulator.

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Table 1.- Delay Times for Each Rise Time and Boom Type

Rise Time, msec	Boom Type	Delay, msec
3	N-wave	0,2,3,4,8,12
3	Minimized	0,2,3,4,8,12
6	N-wave	0,3,5,6,7,12
6	Minimized	0,3,5,6,7,12
9	N-wave	0,3,8,9,10,12
9	Minimized	0,3,8,9,10,12

Table 2.- Correlation Coefficients Between the Logarithms of the Geometric Means and Each Metric for Various Stimuli Set Groupings.

METRIC	ALL BOOMS	N-WAVE BOOMS	MINIMIZED BOOMS
PL	0.9776	0.9796	0.9764
LLZ	0.9606	0.9506	0.9694
L_{AE}	0.9556	0.9508	0.9555
L_{CE}	0.8820	0.8621	0.8995
L_{UE}	0.5706	0.7464	0.8062

Table 3.- Standard Errors of Estimate of the Linear Regression Lines Describing the Relationship Between Each Metric and the Logarithms of the Geometric Means.

METRIC	ALL BOOMS	N-WAVE BOOMS	MINIMIZED BOOMS
PL	0.0380	0.0318	0.0421
LLZ	0.0505	0.0490	0.0479
L_{AE}	0.0532	0.0489	0.0576
L_{CE}	0.0851	0.0800	0.0853
L_{UE}	0.1484	0.1051	0.1156

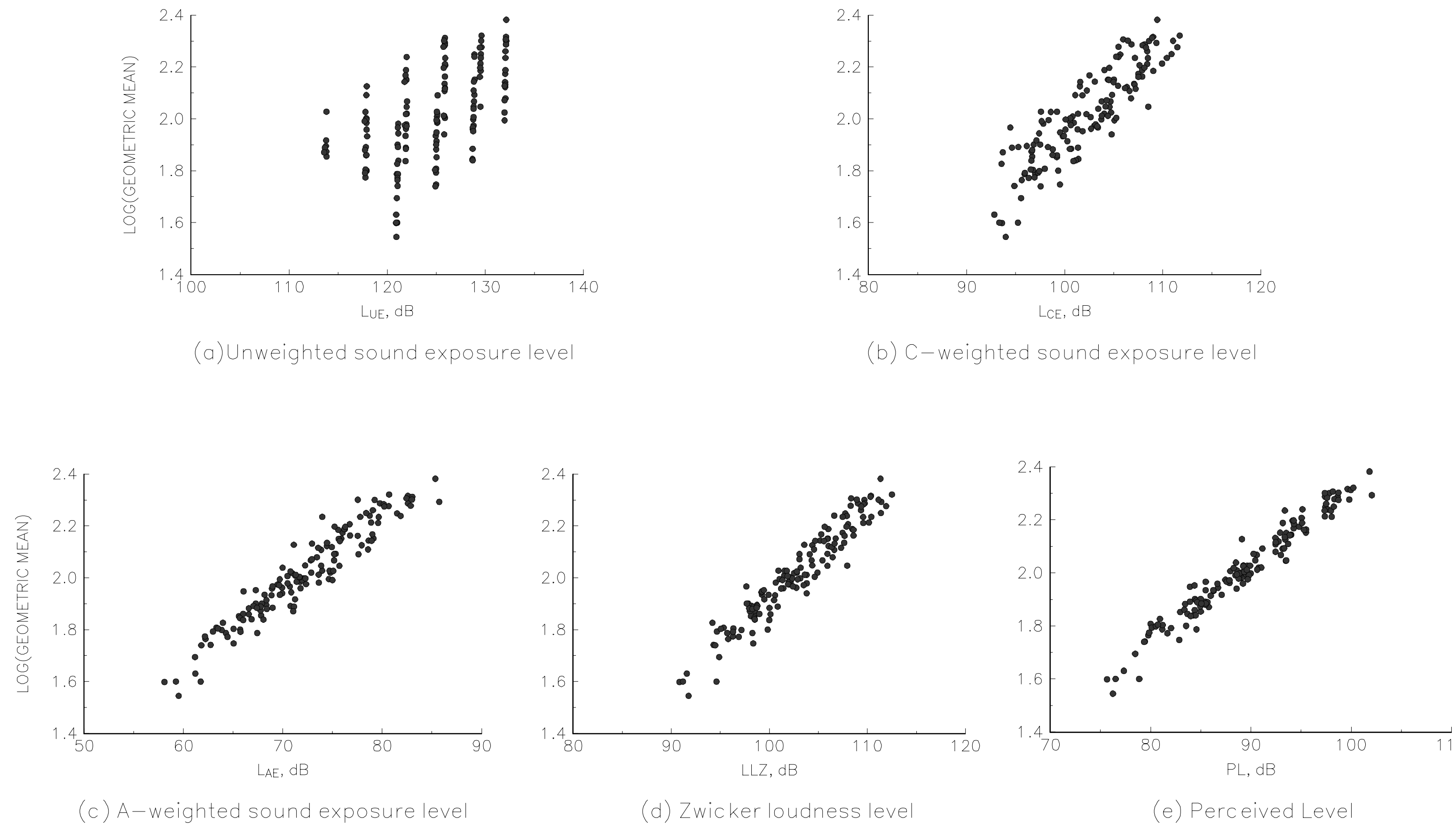

Figure 4.– Scatter plots showing the relationship of subjective loudness judgments to various weighted sound exposure levels and loudness calculations.

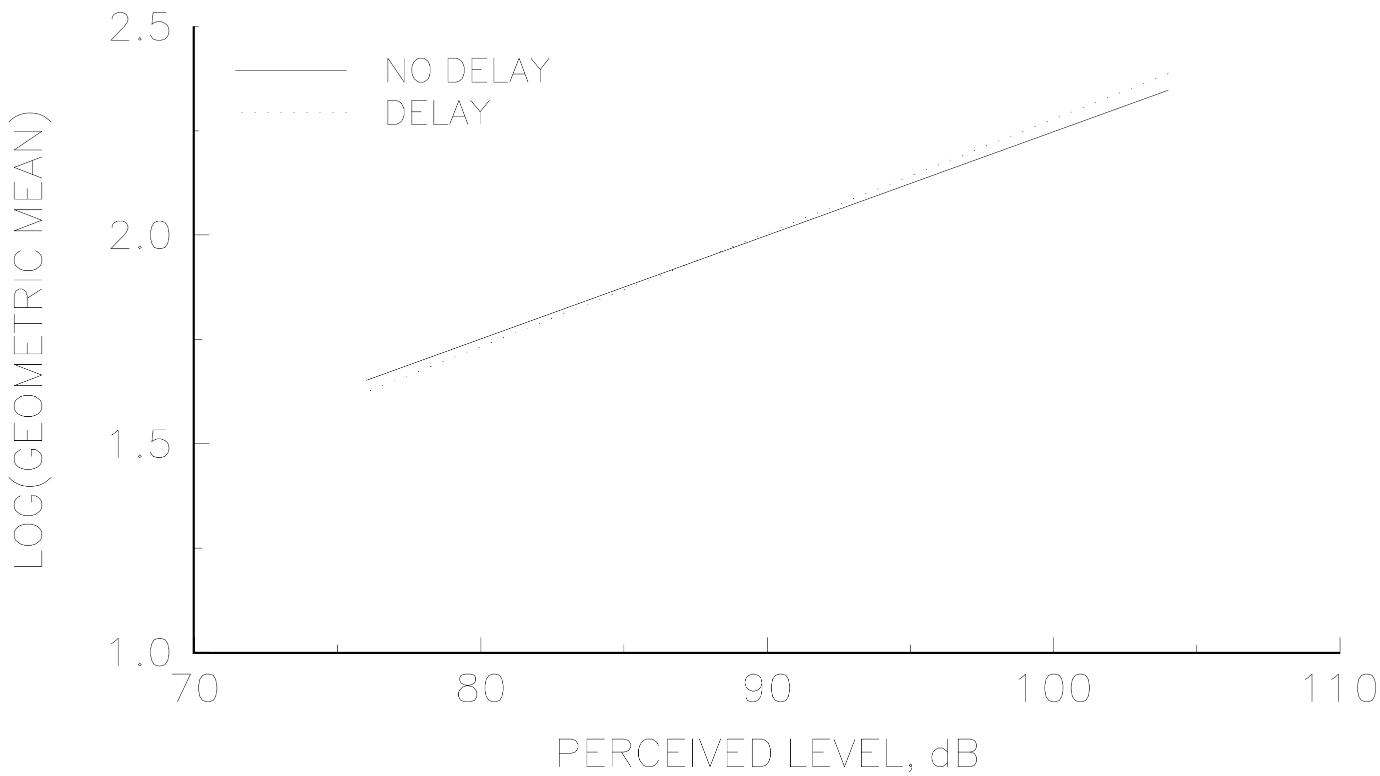

Figure 5.— Comparison of the linear regression lines for the delay and no delay booms

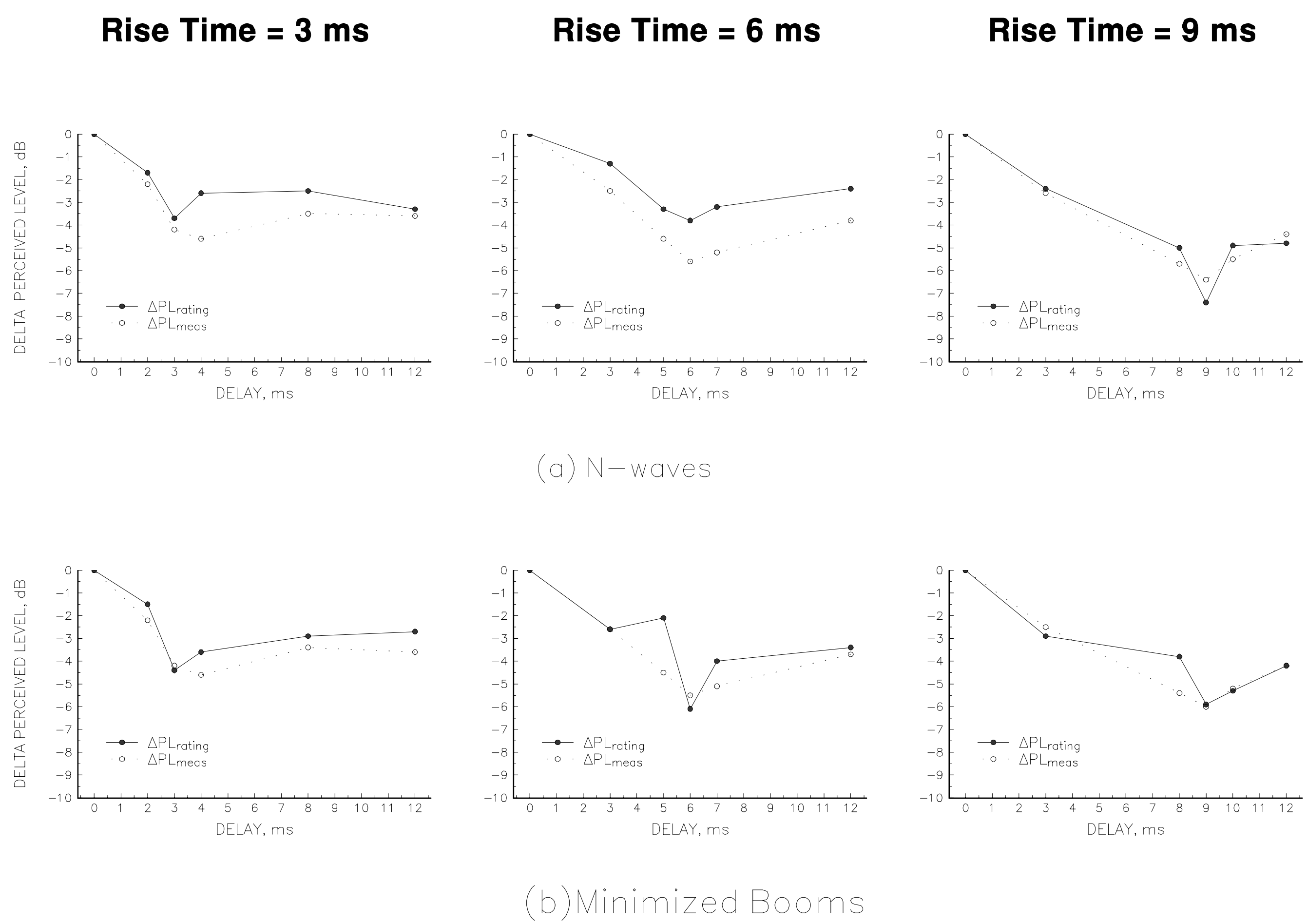

Figure 7.— Delay time effects for each boom shape/rise time combination.